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# LIGHTING CALIFORNIA'S FUTURE: IMPROVED DAYLIGHT PERFORMANCE OF TUBULAR DAYLIGHTING DEVICES

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**California Energy Commission**

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Solatube International Inc.

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## Preface

The California Energy Commission Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

*Lighting California's Future: Improved Daylight Performance of Tubular Daylighting Devices* is the final report for the Lighting California's Future project (Contract Number 500-06-035 conducted by Architectural Energy Corporation, California Lighting Technology Center, and Solatube International. The information from this project contributes to PIER's Building End-Use Energy Efficiency Program.

For more information about the PIER Program, please visit the Energy Commission's website at [www.energy.ca.gov/research/](http://www.energy.ca.gov/research/) or contact the Energy Commission at 916-654-4878.





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## **Abstract**

This project sought to develop commercially available direct/indirect tubular daylighting device diffuser options that significantly reduce direct glare from the diffuser surface. Reducing glare would allow this cost-effective daylighting solution to offer the visual comfort desired by both building occupants and lighting professionals to meet the requirements of many lighting applications. More widespread adoption of tubular daylighting devices would contribute to the larger goal of reducing lighting energy consumption and peak electricity demand.

**Keywords:** Daylighting, glare, tubular daylight devices



# **Executive Summary**

## **Introduction**

Tubular daylighting devices capture light through a dome on a building's rooftop and channel the light into the building through a tube with a reflective interior. Tubular daylighting devices are effective in bringing daylight into a building's interior spaces. The latest reflective tubing technologies are so effective that, with today's commercially available products, the amount of daylight reaching the diffuser (the surface that building occupants see in the ceiling) is so great that it can create visual discomfort, also termed "discomfort glare" or simply "glare."

For this project, researchers at the California Lighting Technology Center partnered with tubular daylighting device manufacturer Solatube International, Inc., to develop a reduced-glare direct/indirect diffuser option for tubular daylighting devices. The California Lighting Technology Center measured and analyzed the performance of current Solatube tubular daylighting devices that use direct diffusers, participated in discussions of desired performance characteristics, and developed criteria for improved direct/indirect diffuser options. California Lighting Technology Center also developed and tested a procedure for simulating proposed diffuser designs using advanced imaging processes, measured and evaluated prototypes that Solatube International designed and built, and made recommendations for further development and testing of the most promising new diffuser design.

## **Purpose**

This project sought to develop commercially available direct/indirect tubular daylighting device diffuser options that significantly reduce glare from the diffuser surface. Reducing glare would allow this potentially cost-effective daylighting solution to offer the visual comfort desired by both building occupants and lighting professionals to meet the requirements of many lighting applications. In combination with turning off electric lights when sufficient daylight is available, more widespread adoption of tubular daylighting devices would help to reduce lighting energy consumption and peak electricity demand.

## **Project Objectives**

This project included the following four objectives:

- Develop conceptual, commercially viable direct/indirect tubular daylighting device diffuser options for detailed photometric analysis.
- Produce two or three commercially viable diffuser options for prototyping, physical testing, and evaluation using performance criteria established by the project team and advisory committee.
- Develop one commercially viable product solution and perform detailed photometric testing and analysis to develop the photometric data required to support and launch the diffuser option to the general public.
- Produce design guidelines to support the application and use, by architecture and lighting design practitioners, of the new commercially viable diffuser option.

## **Project Outcomes**

The primary outcomes of this project are as follows:

- Development of design goals for a new tubular daylighting device direct/indirect diffuser.
- Discovery of the challenges of using ray-tracing software for reproducing results obtained under real sky to determine the optical performance of skylights.
- Development of several prototypes, one of which showed promise to meet the design goals.
- Refinement of the promising prototype and installation in test spaces at the manufacturer's headquarters.
- Identification of additional issues to be resolved with the prototype.
- Recommendations to undertake field testing and perform rigorous comparison testing of the old and new diffuser designs.

## **Conclusions**

Although the new prototype produced for this product represents a step toward meeting the project design specifications, the prototype still produces a lot of glare. With continued refinement of the early prototype designs, this issue could easily be addressed. Incorporation of a new dome and tube design by Solatube International constitutes a potential future-generation "daylight device" which provides increased control of light in the collection and transportation portions of the tubular daylighting device system.

The design process for this project could have been accelerated if photometric simulations using sky-luminance maps, which help simulate the availability of daylight in indoor environments, and a commercially available ray-tracing software program, which models optical systems by analyzing the pathway along which each ray of light travels, had produced reliable results. However, the simulations did not match the measured data. Using computer simulation to develop optical components for skylights required a more in-depth effort than was in the scope of this project.

The inherent variability in light directionality and intensity make consistent optical control of daylight difficult and requires complex optical design and components. Great strides were accomplished by Solatube International to address these design issues. During the project, radical design evolutions occurred to explore the limits of tubular daylighting device light engine collection and transportation, and enhanced optical diffuser technologies. In all, more than twenty diffuser designs were produced for physical evaluation, with one prototype using two different material configurations being applied in test spaces. While the technology is promising, the significant evolution required more time to bring products to market than could be performed given the time frame of this project.

The development of the direct/indirect diffuser prototypes was done by Solatube International's researchers independently from the California Lighting Technology Center researchers, with the latter involved only in performance evaluation. While this kind of arrangement minimizes intellectual property concerns for the manufacturer, in this case, the arrangement probably negatively affected the likelihood of achieving solutions that met the design goals, especially

because the difficulties with the computer simulations significantly reduced the number of design-evaluation cycles.

### **Recommendations**

Photometric simulation programs need further validation to ensure their accuracy for tubular daylighting device design. A project, funded by the California Energy Commission and managed by New Buildings Institute that addresses this issue, is now underway. That project is titled "Enhanced Skylight Modeling and Validation."

The project team recommends that testing of the prototype developed with the enhanced, future-generation Daylight Engine components that were also developed during this project take place side alongside with existing products that have not been modified.

Field testing of the prototype developed in this project is a natural next step and should employ occupants who have worked under existing tubular daylighting device products and who can, therefore, compare experiences of the prototype project to experiences with currently available products. Occupants new to tubular daylighting devices should also be included in the testing.

In the future, closer research industry collaboration could result in greatly improved tubular daylighting device diffuser designs.

### **Commercialization Potential**

With the conclusion of this project, Solatube International has developed direct/indirect diffuser designs that have commercialization potential, but further refinement will be needed to develop products suitable for widespread application. While true direct/indirect diffusers have not been commercially produced, other significant glare reduction advancements developed during this project by Solatube International were successfully launched and commercialized in 2008. These advancements (referred to as future-generation Daylight Engine components) have been widely accepted around the world in visually sensitive environments, being applied to 45 percent of Solatube International's commercial product installations.

At this time, further refinements to the Daylight Engine assembly are also under development, which will further change the design requirements for a commercialized direct/indirect diffuser design. The deployment of additional features in future product designs from Solatube International is expected to even further enhance the adoption of these unique optical-daylighting technologies.

### **Benefits to California**

A successful new tubular daylighting device indirect diffuser design could save significant energy in California. Tubular daylighting devices have the potential to light building cores that are not reachable by conventional skylights or windows. When coupled with control systems that regulate lights in response to daylight levels, tubular daylighting devices that provide daylight to building interiors would save lighting energy. The times of day and year when tubular daylighting devices can provide the most daylight to offset lighting energy use coincide with periods of peak electricity demand. Improving tubular daylighting devices design to make tubular daylighting devices more visually comfortable and, therefore, acceptable to building

occupants would lead to wider adoption, which would benefit electric utilities and electricity grid reliability.

Based on 1 percent market penetration and energy savings potential of 20 percent, when tubular daylighting devices are combined with electric lighting controls, electric consumption savings of 66 gigawatt-hours and demand savings of 8 megawatts could be achieved for large office building and home applications.



## **1.0 Introduction**

### **1.1. Background**

Tubular daylighting devices (TDDs) capture light through a dome on a building's rooftop and channel the light to interior spaces through a tube with an interior reflective system. TDDs are effective in bringing daylight into a building's interior spaces. The latest reflective tubing technologies are so effective that, with today's commercially available products, the amount of daylight reaching the diffuser (the surface that building occupants see in the ceiling) is so great that it can create visual discomfort, also termed "discomfort glare" or simply "glare."

For this project, researchers at the California Lighting Technology Center (CLTC) partnered with TDD manufacturer Solatube International, Inc., to develop reduced-glare direct/indirect diffuser options for Solatube TDDs. The CLTC measured and analyzed the performance of current Solatube TDDs that use direct diffusers, participated in discussions of desired performance characteristics and criteria for improved diffuser options, developed and tested a procedure for simulating proposed diffuser designs using high dynamic range imaging processes, measured and evaluated prototypes that Solatube International designed and built, and made recommendations for further development and testing of the most promising new diffuser design.

### **1.2. Project Objectives**

This project includes the following four objectives:

- Develop conceptual, commercially viable direct/indirect TDD diffuser options for detailed photometric analysis.
- Produce two or three commercially viable diffuser options for prototyping, physical testing, and evaluation using performance criteria established by the project team and advisory committee. Photometric analysis indicated that the options should produce a minimum of 40% uplight component.
- Develop one commercially viable product solution and perform detailed photometric testing and analysis to develop the photometric data required to support and launch the diffuser option to the general public.
- Produce design guidelines to support the application and use, by architecture and lighting design practitioners, of the new commercially viable diffuser option.

### **1.3. Benefits to California**

A successful new TDD indirect diffuser design could save significant energy in California. TDDs have the potential to light building cores that are not reachable by conventional skylights or windows. Using daylighting in these interior building zones would save lighting energy when coupled with control systems that regulate electric lights in response to daylight levels. The times of day and year when TDDs can provide the most daylight to offset lighting energy use coincide with periods of peak electricity demand. Improving TDD design to make TDDs more visually comfortable and therefore acceptable to building occupants would lead to wider adoption, which would benefit electric utilities and electricity grid reliability.

Based on one percent market penetration and energy savings potential of 20%, when TDDs are combined with electric lighting controls, electric consumption savings of 66 GWh (GigaWatt-hours) and peak demand savings of 8 MW (MegaWatts) could be achieved for large office building and residential applications.

Solatube International appreciates the opportunity to participate in the PIER Lighting California's Future (LCF) program. Program participation has enabled the accelerated development of new technologies for the TDD category that can be applied to current and future product offerings. The technologies developed and released during this project not only enhance the visual comfort of the TDD products, but have also enabled key thermal and solar advancements to occur furthering the energy and environmental performance goals of California and the Department of Energy. These advancements have been acknowledged in the commercial market as key improvements and have increased the acceptance and adoption of optical top-lighting technologies in most commercial building types. This also greatly increases the perceived and real usability of TDD products as a viable daylighting technology.

## **1.4. Report Organization**

The organization of the remainder of this report is as follows:

Section 2.0 – Project Approach describes the methods used to simulate and measure the performance of existing and prototype TDDs.

Section 3.0 – Project Outcomes describes the results of the project work.

Section 4.0 – Conclusions and Recommendations presents the conclusions drawn from the project research and the CLTC team's recommendations for future work.

Section 5.0 lists the references relevant to this project.

Appendix A describes details of the simulation method developed for TDDs using commercially-available ray-tracing software.

## 2.0 Project Approach

Researchers from the CLTC partnered with TDD manufacturer Solatube International for this project. Table 1 shows the project tasks and responsible partners.

**Table 1. Project Tasks and Responsible Partners**

Task	Responsible Partner
Measure current daylight distribution of Solatube skylights	CLTC
Design optical elements that will improve distribution	Solatube International
Simulate daylight distribution using ray-tracing software	CLTC
Evaluate simulation results	CLTC
Refine and evaluate improved diffuser design	Solatube International/CLTC
Develop prototype of final design	Solatube International
Demonstrate performance of prototype	Solatube International/CLTC
Conduct discussions with utility emerging technology staffs	Solatube International
Conduct project-level market connections activities (see the Final Report for Project 11, <i>Market Connections</i> )	CTLC

Source: California Lighting Technology and Solatube International

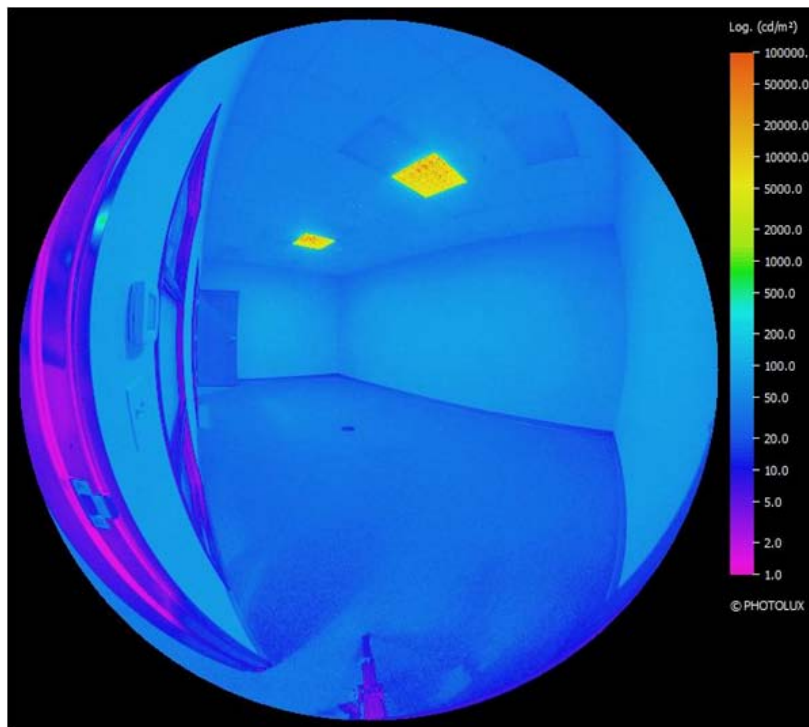
### 2.1. Measurement and Simulation of TDD Performance

In July 2007, CTLC researchers performed initial measurements of Solatube TDDs using the first-generation Daylight Engine (dome and tubing assembly) under sunny skies at Solatube headquarters in Vista, California. Figure 1 shows a fish-eye image of a space at Solatube International headquarters illuminated by a TDD at that time. Figure 2 shows the corresponding luminance map. The maximum luminance of this existing product with a direct diffuser was 86 kilocandelas per square meter (kcd/m<sup>2</sup>). This is significantly brighter than the luminance of a typical T8 fluorescent lamp, which is in the range of 15 kcd/m<sup>2</sup>. Visible in the image are the typical hot spots within the visible area of the TDD.



**Figure 1. Luminance camera view of TDD with industry-standard dome and diffuser**

Source: California Lighting Technology and Solatube International



**Figure 2. July 2007 glare measurement results for TDD with industry-standard dome and diffuser**

Source: California Lighting Technology and Solatube International

Based on these initial measurements, the Solatube design team, with input from CLTC, selected 20 – 30 kcd/ m<sup>2</sup> as the target maximum luminance for an improved TDD with indirect diffuser. At this luminance, the product would still create glare, but it would create much less than the existing direct diffuser, and still elicit the occupants’ perception that the space is daylighted. Table 2 shows the initial product specifications.

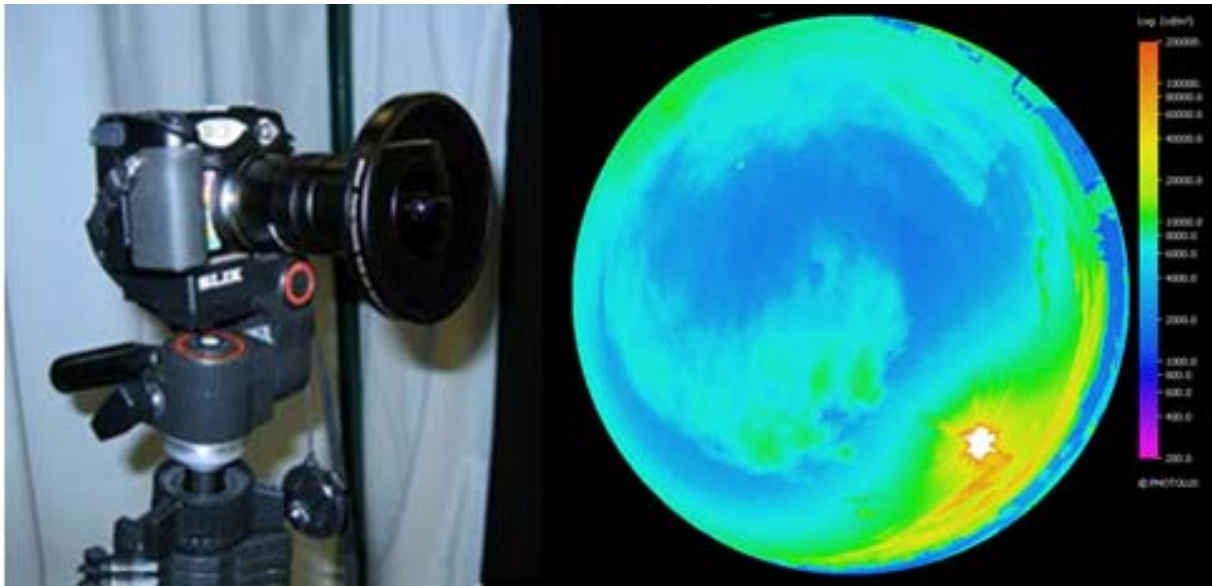
**Table 2. Initial product specifications for new prototype direct/indirect TDD diffuser**

<b>Performance Goals</b>
<p>Desired Spread of Light</p> <p>Cast light evenly on ceiling plane up to 7-feet from fixture center</p> <p>Support fixture spacing of 10’ – 12’ on center</p>
<p>Acceptable Suspension/Pendant Length</p> <p>Ideal: 6” – 12”</p>
<p>Ceiling Contrast Uniformity</p> <p>Benchmark Criteria: Range of 15:1 to 20:1 for daylight source</p>
<p>Max Luminance of Fixture</p> <p>Benchmark Criteria: Range of 20,000 to 30,000 cd/m<sup>2</sup> for daylight source</p>
<p>Visual Comfort Probability (VCP) and/or Universal Glare Rating (UGR)</p> <p>UGR ≤ 19 (CIE max recommendation for office space)</p> <p>VCP ≥ 70</p>
<p>Light Distribution (Up to Four Options) Not to Limit “View of Sky”</p> <p>Direct/Indirect: 80% Downlight / 20% Uplight and 60% Downlight / 40% Uplight</p> <p>Indirect/Direct: 40% Downlight/ 60% Uplight and 20% Downlight / 80% Uplight</p>

To accelerate the design process, CLTC researchers used lighting-simulation software to determine the performance of a sample Solatube TDD installed at the Western Cooling Efficiency Center (WCEC) at the University of California, Davis. Simulations would have allowed the design team to evaluate more configurations more rapidly than would be possible by building and measuring prototypes. Simulations also have the advantage of controllable conditions, in contrast to prototype testing, which is limited by available weather and exterior obstructions.

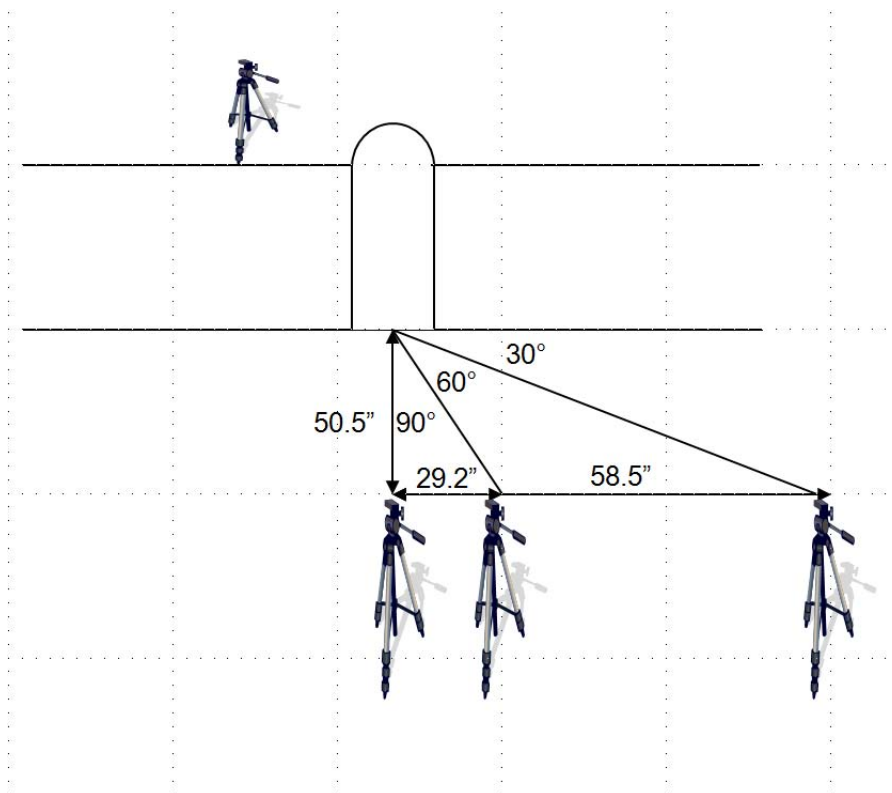
To validate the simulation method, CLTC researchers also measured the optical performance of the Solatube TDD that was modeled in the simulation software. The procedure for measuring the optical performance of the WCEC installation entailed one researcher using a luminance camera and an illuminance meter on the roof to take a luminance map of the sky while simultaneously a second researcher, using another luminance camera inside the building, measured the luminance of the TDD equipped with standard diffuser. The camera’s fish-eye lens is capable of capturing the whole hemisphere of the sky.

Figure 3 shows the luminance-mapping camera setup and a sample sky luminance distribution. The saturated area of the image corresponds to the sun and circumsolar region. Figure 4 illustrates the method of simultaneous measurements on the rooftop and in the building’s interior space.



**Figure 3. Luminance camera setup and sample sky luminance map**

Photo Credit: California Lighting Technology and Solatube International



**Figure 4. Simultaneous rooftop sky imaging and interior TDD imaging method**

Source: California Lighting Technology and Solatube International

Figure 5 shows the installation of the existing Solatube TDD with direct diffuser at WCEC. Figure 6 shows a sample of the luminance camera images from the rooftop sky luminance imaging at WCEC. In each image, the sky luminance map appears on the left, and the TDD

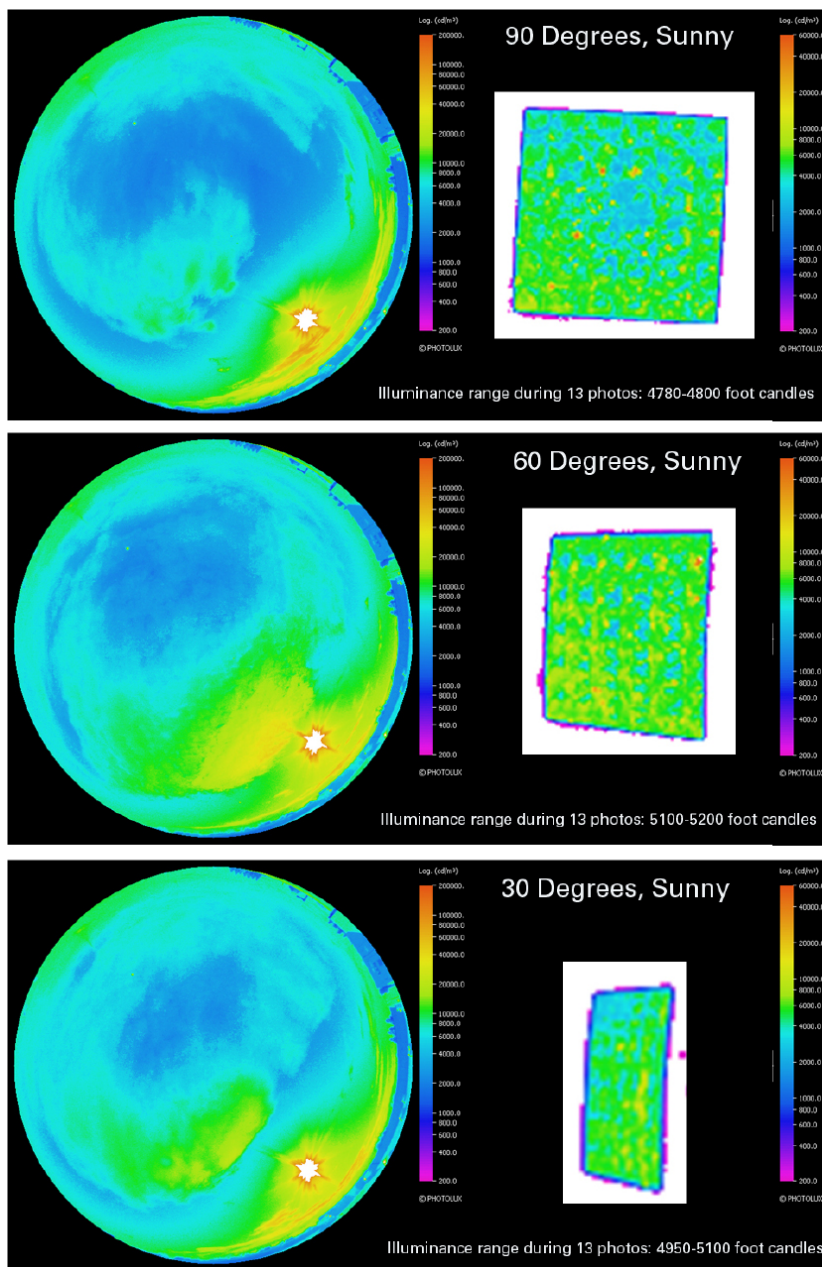
diffuser luminance map, as seen from inside the building, appears on the right. Researchers took measurements of the TDD at several angles along with sky images simultaneous with the TDD images. Solatube provided a three-dimensional computer-aided design (CAD) drawing with the same geometry as the measured TDD.



**Figure 5. Solatube TDD with standard direct diffuser and first-generation Daylight Engine, installed at WCEC**

Source: California Lighting Technology and Solatube International





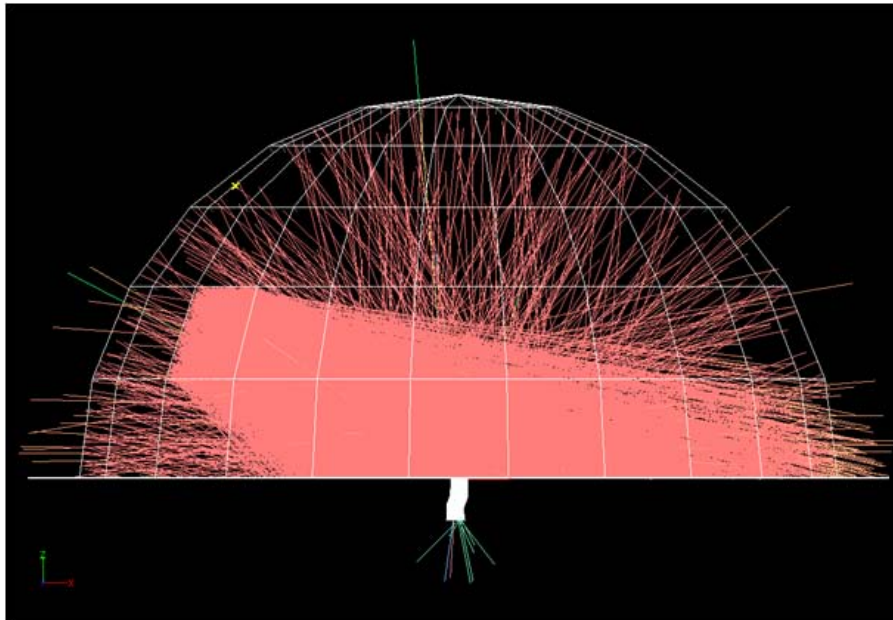
**Figure 6. Luminance image from WCEC measurements. Saturated region corresponds to the sun and circumsolar region**

Source: California Lighting Technology and Solatube International

The CLTC researchers input the sky luminance data and the estimated materials properties for the TDD with direct diffuser into a commercially-available lighting-simulation program called Photopia<sup>1</sup>. For this end, the standard sky models available in Photopia had to be modified. Figure 7 shows an image of the Photopia model of the sky dome with the TDD visible below. See Appendix A for details of the simulation method.

<sup>1</sup> Photopia is a product of LTI Optics, <http://www.lti optics.com/Photopia/overview.html>



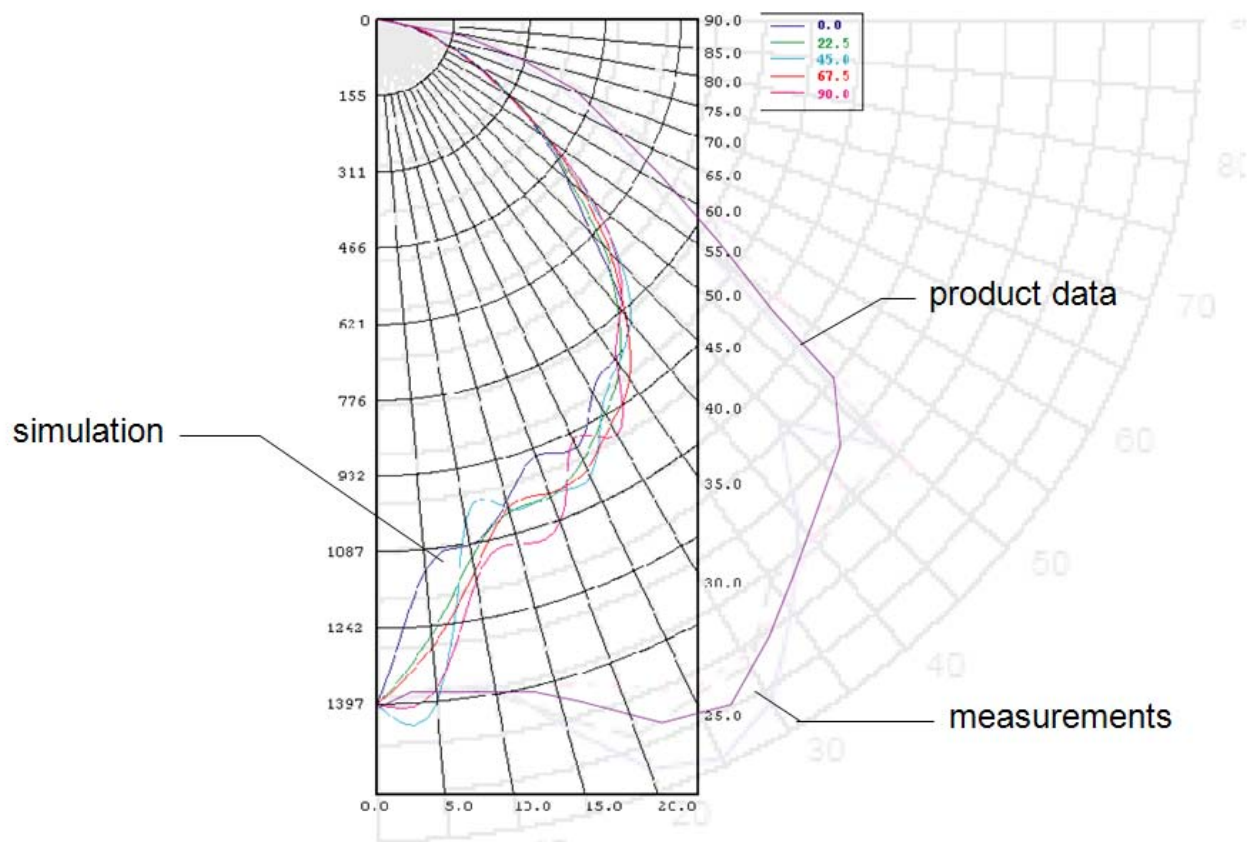


**Figure 7. Photopia model of sky dome, with most rays emanating from sun (at left), and TDD below the horizontal white line**

Source: California Lighting Technology and Solatube International

The simulation results did not correspond to the measured data for the TDD. Although the order of magnitude was correct, the shape of the intensity distribution was very different. Figure 8 shows the difference between the measured and simulated data and the similarity between the measured data and the manufacturer's data. Because the measured results closely matched the manufacturer's data, the team concluded that the measurement procedure used was accurate and that it was the simulation process that needed more development in order to be accurate.

There were a number of possible explanations for the failure of the simulations to match the measured data, including the discretization of the sky dome, the lack of measured bidirectional optical properties of the TDD materials, and the complexity of the diffuser CAD model, which at times required a degree of computational capability that exceeded available resources.



**Figure 8. Comparison of simulation results (multi-colored lines), manufacturer's data (purple line), and measured data (red points). The Y axis represents luminous intensity in candelas, and the X axis represents altitude angle in degrees.**

Source: California Lighting Technology and Solatube International

The scope of the project did not permit further efforts to improve and validate simulations, so the team proceeded by using measurements of actual installations and prototypes. After 12 months, Solatube International provided several prototypes, one of which showed promise and had a maximum luminance close to the design goal range of 20-30 kcd/m<sup>2</sup>.

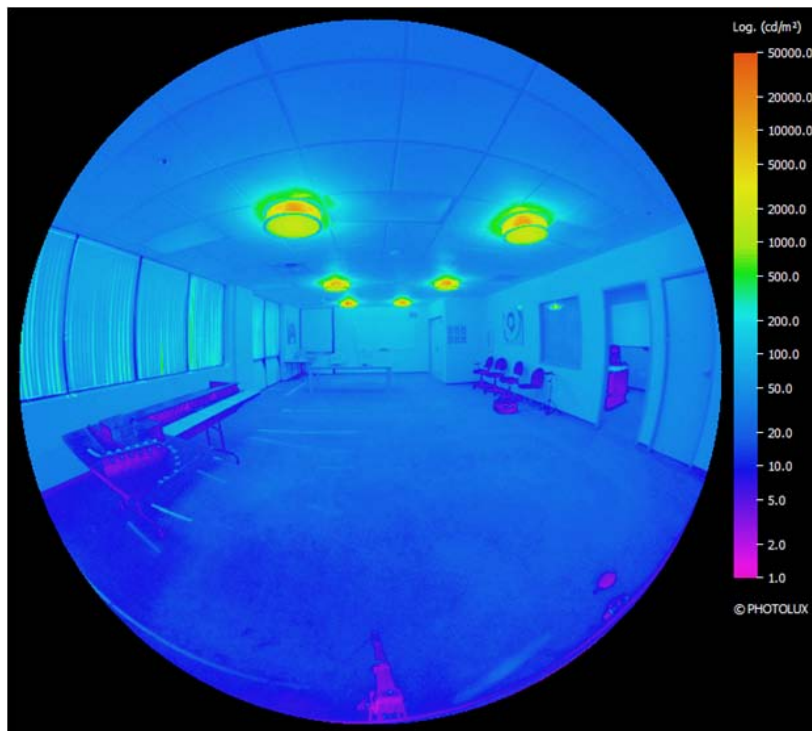
Solatube International further refined this prototype and installed it at their headquarters in two settings: 1) open-plan office, side by side with TDDs using the original diffuser and 2) a private office. In addition to the new diffuser, the new prototype also used a new dome and tube design (future-generation Daylight Engine) that improved light distribution. The CLTC staff performed luminance measurements of both diffusers in October 2009.

Figure 9 shows the new prototype diffuser with new tube and dome, installed at the Solatube International headquarters. Figure 10 shows the luminance measurement results for the new prototype.



**Figure 9. New prototype TDD with new dome, tube, and diffuser**

Source: California Lighting Technology and Solatube International



**Figure 10. Luminance image and measurements for new prototype with new dome, tube, and diffuser**

Source: California Lighting Technology and Solatube International

## **2.2. Design and Evaluate Optical Elements**

This project started using the first-generation Daylight Engine to develop new indirect technologies to diffuse daylight in a space, thereby providing improved visual comfort. The inherent variability in light directionality and intensity makes consistent optical control of daylight difficult and requires complex optical design and components. Great strides were accomplished by Solatube International to address these design issues.

Initial designs revealed that optical control could not be effectively implemented to remove shifting patterns of light from occurring on the ceiling plane because of the inconsistency of the daylight source. As a result, a significant effort ensued to develop new Daylight Engine technologies which build upon current Solatube International patents. This approach enabled the development of technologies to significantly improve upon angular selection and control of the daylight source, as well as improve upon angular control of light as it reflects down the TDD tubing system. These two innovative optical enhancements provided strict optical control and input of light to the diffuser assembly, thereby improving the control and predictable delivery of daylight to the occupied space and ceiling plane.

## **2.3. Develop and Evaluate Prototypes**

The development of a solution to achieve a balance between light redirection and output while masking hot spots was difficult. Diffuser options were developed that incorporated both optical reflectors and visual shielding technologies. In all, over twenty diffuser designs were produced for physical evaluation, with one prototype using two different material configurations being applied in test spaces.

Prototype evaluations studied both reflective surface specularly of internal optical elements and the diffusion and shielding characteristics of external housing elements (i.e. diffusing films to remove views of optical hotspots and perforated materials to control contrast). The ability to find an optimal combination of these design elements was not reached within the timeframe of this project.

In October 2009, Solatube International developed six prototypes of the favored direct/indirect product solution and applied them to an existing open plan office configuration within the Solatube International Product Development office. This application allowed the products to be visually and photometrically studied over a prolonged period of time and their performance was ultimately documented by the CLTC staff (reference Figures 9 and 10 from Section 2.1).

On October 21, 2009, the PIER team held a prototype review meeting at the Solatube International offices in Vista, California to review the results of the new prototypes as compared to the program objectives. It was determined that the new prototypes met the objective for spread of light, pendant length, and ceiling uniformity. However, continued prototype refinement would be necessary to meet the ultimate glare objectives of the project. As a result of the significant improvements to the reduction of glare, it was determined that the developed prototypes might be suited for applications with higher ceilings (greater than 10 feet) since the viewing angles afforded via higher ceilings resulted in better visual shielding of potential hot spots on the internal reflector elements.

Ultimately, the need to incorporate a future generation Daylight Engine was an unexpected developmental issue that affected Solatube International's ability to develop commercially viable diffuser offerings within the timeframe of this PIER project. While the technology is promising, the significant evolution required more time to bring products to market than could be performed given the time frame.



### 3.0 Project Outcomes

The primary outcomes of this project are as follows:

- Development of design goals for a new TDD direct/indirect diffuser.
- Discovery of the challenges of using ray-tracing software for reproducing results obtained under real sky to determine the optical performance of skylights.
- Development of several prototypes, one of which showed promise to meet the design goals.
- Refinement of the promising prototype and installation in test spaces at the manufacturer's headquarters.
- Identification of additional issues to be resolved with the prototype.
- Recommendations to undertake field testing and perform rigorous comparison testing of the old and new diffuser designs.

Although the new prototype direct/indirect diffuser does not display the extremely bright hot spots that are characteristic of the original diffuser, very bright areas are still visible. Additionally, because the new diffuser protrudes into the interior space below the surface of the ceiling, it is a larger object in the building occupants' field of view than the old diffuser, which was flush with the ceiling surface, and it can still cause significant glare. In the installation in an individual office setting, the new TDD appears more visually comfortable than the original TDD, at least for the first few minutes an occupant is in the room.

The measurements indicate that the new system's maximum luminance ( $26 \text{ kcd/m}^2$ ) is about half of the maximum luminance of the original system ( $57 \text{ kcd/m}^2$ ). The absolute values of these measurements are not strictly comparable to those shown in Figure 2 because of the significant difference in sun position and intensity between October (when researchers measured the new prototype) and July (when researchers measured the original system, the maximum luminance exceeded  $80 \text{ kcd/m}^2$ ). Furthermore, the fact that the new prototype was fitted with the future generation Daylight Engine in addition to the new diffuser introduces the possibility that at least some of the reduction in luminance is not due completely to the new diffuser.

The average luminance for the area of the field-of-view subtended by the diffuser is significantly lower for the new system, which significantly lowers the ratio of average fixture luminance to the darkest parts of the ceiling in between fixtures (approx. 216:1 for the original TDD, 76:1 for the new prototype). However, computed glare indices (Unified Glare Rating) are similar for both systems—in the range of 23-24—which is well above the maximum recommended value of 19 for offices.

For some applications such as individual offices, the new product with indirect diffuser utilizing a future generation Daylight Engine may improve visual comfort. However, it still falls short of the quantitative goals set at the beginning of the project. A natural next step would be to demonstrate the new product in the field, both with building occupants familiar with the current TDD product and with occupants not familiar with TDDs, in order to determine whether the developed direct/indirect diffuser results in increased acceptance.

At present, producing more prototypes for a field demonstration is not part of Solatube International's plans. Although the ultimate goal and desire of this project was to apply the

technologies developed to a demonstration project, it was determined that the viability of retrofitting an existing installation would be problematic because of the extent of changes to the Daylight Engine. As an alternative demonstration, it was proposed to apply the components that were released in 2008 during this program to an existing space and conduct detailed building analysis and occupant surveys to assess the improvements and their acceptance by building occupants as well as study the energy savings related to applying this enhanced daylighting solution. Unfortunately, the selected site was unable to make the necessary modifications to their existing lighting system necessary to complete the study in the allotted time.



## 4.0 Conclusions and Recommendations

### 4.1. Conclusions

Although the new prototype produced for a TDD product represents a step toward meeting the design specification for the project, it still produces glare. Moreover, the incorporation of a future generation Daylight Engine with the new diffuser in the prototypes produced for this project made it difficult to isolate the impact of the new diffuser in reducing glare.

Photometric simulations using lighting-simulation software would have enabled a more rapid design process for this project. With the available resources, however, the simulation process did not produce accurate results when compared with measured data, using the simulation software tools that were available at the time. Since the start of this project and the time when the initial photometric studies were initiated, significant advancements have been made in the ability to perform photometric modeling of advanced TDD systems, incorporating new, more exacting processes for inclusion of actual sky maps. To use photometric simulations to develop optical components for skylights requires more in-depth validation than was possible for this project, in addition to more precise data about product materials.

The significant evolution of the TDD Daylight Engine that occurred simultaneously during the direct/indirect diffuser development process provides new and critical optical control of the constantly variable daylight resource that is necessary to provide the necessary controlled optical input to the diffuser's daylight delivery system. With the optical control afforded by the future-generation Daylight Engine, it was shown that the potential for shifting patterns of redirected light across the ceiling plane was substantially reduced. This greater optical control also allows for improved optical design of the direct/indirect diffuser's optical elements, since the variability of daylighting input angles to the diffuser's optical system was greatly reduced.

In all, more than twenty variations of direct/indirect and indirect/direct diffuser design were designed, constructed, and field-observed/tested by Solatube International at its Vista, California-based Product Development facility. The field measurement of the various direct/indirect diffuser prototypes clearly indicate the viability of direct/indirect diffuser options, and their ability to reduce potential glare to acceptable levels in visually-critical environments, when paired with the future generation of TDD Daylight Engines. Unfortunately, the concurrent and significant evolution of the Daylight Engine system forced delays in Solatube International's diffuser design and testing schedule, which impacted the ability to produce final, acceptable diffuser products in the project's timeframe.

The development of these direct/indirect diffuser prototypes was done by Solatube International's researchers independently from the CLTC researchers, with the latter only involved in performance evaluation. While this kind of arrangement minimizes intellectual property concerns for the manufacturer, in this case, it probably negatively impacted the likelihood of achieving solutions that met the design goals, especially because the difficulties with the computer simulations significantly reduced the number of design-evaluation cycles.

## **4.2. Recommendations**

The results obtained in this project indicate that the use of lighting simulation programs to determine the lighting performance of TDDs needs further validation to ensure its accuracy for product design purposes.

Since the luminance measurements of the direct/indirect diffuser prototype were conducted by being mounted on a TDD that also had an improved dome and tube, it would be valuable to repeat these measurements side by side with a direct diffuser mounted on the same type of dome and tube, so that the performance of the two diffusers can be directly compared.

It would be very valuable if the prototype developed in this project were tested in a field setting. This would be best done with both occupants who have worked under existing TDD products and occupants new to TDDs. This could provide a sense of whether the prototype represents an improvement over existing TDD diffusers, and may help to understand the level of acceptability of this kind of product to the general public.

In future product research and development, a more collaborative industry-university design process will probably be more likely to achieve solutions that meet the design goals.

## **4.3. Commercialization Potential**

As of the conclusion of this project, Solatube International has developed product designs that have commercialization potential, but further refinement will be needed in order to develop products suitable for wide-spread application. At this time, further refinements to the Daylight Engine assembly are also under development, which will further change the design requirements for a commercialized direct/indirect diffuser design.

Solatube International recognizes the value and potential of the new technologies explored, developed, and evaluated during this project; and portions of the technologies developed have already been deployed and additional features are currently being incorporated into future product design. While true direct/indirect diffusers have not been commercially produced, other significant glare reduction advancements developed during this project by Solatube International were successfully launched and commercialized in 2008 as the future generation Daylight Engine , and have been widely accepted around the world in visually sensitive environments. The market need for these advanced technologies has been demonstrated through the fact that 45% of Solatube International's commercial product installations incorporate portions of these new product offerings. The deployment of additional features in future product designs from Solatube International is expected to even further enhance the adoption of these unique optical-daylighting technologies.

## **4.4. Benefits to California**

Tubular daylighting device systems have potential to light the building core, which is not reachable by conventional skylights or windows. When TDDs are coupled with control systems that dim electric lights in response to daylight levels, the resulting lighting energy savings are greatest at times of peak electricity demand. A reduced-glare TDD will likely be more widely accepted by building occupants than current products because of increased visual comfort and

therefore result in greater lighting energy savings than are possible with today's commercially-available products.

Based on one percent market penetration and energy savings potential of 20%, when TDDs are combined with electric lighting controls, electric consumption savings of 66 GWh (GigaWatt-hours) and peak demand savings of 8 MW (MegaWatts) could be achieved for large office building and residential applications.



## Glossary

Specific terms and acronyms used throughout this work statement are defined as follows:

Acronym	Definition
AEC	Architectural Energy Corporation
CAD	Computer-aided Design
CIE	<i>Commission Internationale de l'Éclairage</i> : the International Lighting Commission
CCT	Correlated Color Temperature
Commission	California Energy Commission
CLTC	California Lighting Technology Center
CFL	Compact fluorescent lights
CRI	Color rendering index
DR	Demand response
FC	Footcandles
GW	Gigawatt
IES	Illuminating Engineering Society
K	Kelvin temperature
kcd/m2	Kilocandelas per square meter
LM	Lumens
LPD	Lighting power density
kW	Kilowatt
kWh	Kilowatt-hour
M&V	Measurement & verification
mA	Milliamps
MW	Megawatt
MWh	Megawatt hour
N/A	Not available
M&V	Measurement & verification
PIER	Public Interest Energy Research
TDD	Tubular Daylighting Device
Title 24	California Non-Residential Energy Efficiency Building Standards
TOU	Time of use (electricity rate)
UGR	Universal glare rating
VCP	Visual Comfort Probability
Vdc	Volts direct Current
W	Watts
W/sqft	Watts per square foot
WCEC	Western Cooling Efficiency Center



## Appendix A

This appendix describes the method used to enter measured sky luminance data into the ray-tracing software Photopia.

Photopia contains a sky dome model for daylighting calculations, shown in Figure 7 in this report. In this model, the sky hemisphere is divided into trapezoidal sections and includes a separate surface for the sun. For this project, the team removed the sun from the model because the sun was included in the sky dome photos.

To obtain the luminance distribution of the sky, the team used Photolux, a commercial luminance mapping system. This system takes a series of images taken at different exposures with a Nikon Coolpix 5400 digital camera, fitted with a fish-eye lens, and produces false-color images of the luminance distribution in the camera's field of view. Photolux can export this luminance in various formats. For this project, the team used luminance data from the sky in one-degree increments, both altitude and azimuth, which is the highest resolution that Photolux exports.

The areas of the luminance maps that correspond to the sun and circumsolar area are saturated; no luminance data can be obtained for those areas with the images taken by the camera. To correct for this, simultaneous measurements of global horizontal illuminance were taken with a Minolta CL-200 illuminance meter. The average luminance of the saturated area of the luminance maps was then calculated by determining the difference between the measured horizontal illuminance and the horizontal illuminance calculated by Photolux based on the sky luminance distribution. This difference was converted into an average luminance using the following expression:

$$(1) \quad L_{sat} = \frac{\Delta E_{gh}}{\Omega_{sat} \cos \xi}$$

Where  $L_{sat}$  is the average luminance of the saturated area of the luminance map,  $\Delta E_{gh}$  is the difference in global horizontal illuminance between the illuminance meter and Photolux,  $\Omega_{sat}$  is the solid angle subtended by the saturated area and  $\xi$  is the angle between the center of the saturated area and the zenith.

Once the luminance map of the sky was completed as described above, the average luminance of each of the trapezoidal patches that compose the Photopia sky model was calculated by averaging the luminance of the points of the  $1^\circ \times 1^\circ$  grid that corresponded to each patch.

The final step was to modify the text files that underlie the Photopia sky model so that each patch emitted the appropriate number of rays. Each of these text files contains the luminance of a single surface of a light source in Photopia. The file associated with each sky patch usually contains the luminance of that patch according to standard sky models. For the purposes of this project, the luminance value in each file was replaced with the value derived from the sky luminance map corresponding to the position of the patch. A second type of file, the luminaire definition file (LDF), was also updated with the total amount of flux emitted by the complete array of patches.